CHAPTER 33

ION BEAM REQUEST AND OVERVIEW

33.1 LHC BASELINE BEAM REQUEST

The main LHC client requesting high-luminosity running with Pb ions is ALICE, but more recently CMS and ATLAS have also expressed their interest. Pb-Pb collisions are the priority for the first 2-3 years of ion operation. Next on their programme are proton-lead collisions for 1-2 years, followed by lighter ion colliding beams about five years after ion start-up [1]. Clearly there is time left to deal with the lighter ions at a later stage, once one has learned about the issues of Pb ions in the LHC.

The principal LHC Lead ion beam parameters required to attain the design luminosity per experiment, $L = 10^{27}$ cm^{-2} s^{-1}, are given in Tab. 33.1.

Table 33.1: Lead nominal (baseline) parameters in LHC at collision

Parameter	Unit	Value	Comments
energy/nucleon	TeV/n	2.76	
initial luminosity L_0	cm^{-2} s^{-1}	10^{27}	
number of bunches/bunch harmonic		592/891	
bunch spacing	ns	100	
β^*	m	0.5	about same as p
crossing angle	μrad	80	
number of Pb ions/bunch		7×10^7	
transverse emittance (norm., rms)	μm	1.5	same physical emittance as p for same Bρ
rms beam radius at IP	μm	16	same as p
longitudinal emittance/charge	eVs/charge	2.5	
rms bunch length	cm	7.5	
L half-life (2/3 experiments)	h	4.6/3.1	

The LHC baseline parameters for lead ions strike a balance between high luminosity and several fundamental limitations [2, 3].

33.1.1 Limitations in LHC

Electromagnetic interactions limit luminosity

Colliding ions changing their charge/mass ratio: during a store, peripheral collisions between $^{208}\mathrm{Pb}^{82+}$ ions may lead to the loss of a neutron (→ $^{207}\mathrm{Pb}^{82+}$ by electromagnetic dissociation) or to capturing an electron after pair production (→ $^{208}\mathrm{Pb}^{81+}$, cross section ~280 barns). Both processes give rise to a change in momentum/charge. While the ions losing a neutron are intercepted by the collimators, the ones having captured an electron (momentum/charge changed by > 1%) are likely to be lost in a superconducting dipole of the dispersion suppressor. A magnet quench may then occur at a luminosity of as low as 4×10^{26} cm^{-2} s^{-1}, potentially limiting the LHC Pb design performance (see Vol. 1, Chap. 21). However, there are some safety factors in hand.

Marginal sensitivity of position monitors

The nominal LHC ion bunch intensity in collisions, 7×10^7 Pb ions/bunch (~6×10^9 charges/bunch) is still visible on the beam position monitors (BPM). During the store, this bunch population may decrease below their initial sensitivity of 4×10^9 charges/bunch; a recent upgrade of the electronics has set this limit to ~2×10^9 charges/bunch [4] and provides somewhat more margin.

Luminosity lifetime

During a store, the luminosity is deteriorated mainly by particle losses due to ion-ion collisions, with a somewhat weaker contribution due to transverse emittance growth caused by Intra-Beam Scattering (IBS).

This lifetime is roughly inversely proportional to the number of high-luminosity experiments and as low as 3 hours with 3 of them.

Transverse emittance same as protons

The ions have to be accommodated into the LHC dynamic aperture, in much the same way as the protons, thus the ion *physical* emittance is designed to match the one for protons at any given magnetic rigidity (for example at LHC injection and collision energies).

Each LHC ring will be filled with almost 600 Pb ion bunches. Contrary to proton-proton collisions, the ion experiments are rather relaxed in terms of bunch-to-bunch intensity variations because the ion event rate is much lower than the bunch repetition frequency; however, limitations in the ion injector chain define a tolerance of about ±20%.

33.2 INJECTOR CHAIN: OVERVIEW, LIMITATIONS

The LHC injector chains for protons and Pb ions are identical except for the first two accelerators: proton Linac2 is replaced by heavy ion Linac3 and the PSB by LEIR. For lead ions, the intensity/emittance ratio achievable via the PSB falls short of LHC specifications by a factor ~30, hence the proposal to use phase space cooling to make up for this factor. The ion injector chain is pivoting on LEIR, the (mothballed) LEAR after substantial upgrading, with a new powerful electron cooling system as key ingredient. The device enables accumulation of 4-5 pulses from Linac 3 to obtain an adequate intensity (10^9 Pb ions) and beam cooling in all three phase planes so as to squeeze these ions into very small emittances ($\varepsilon^*_{\text{rms}} \sim 0.7\ \mu$m).

The parameters of the lead ion injector chain are restrained by several basic limitations.

33.2.1 Limitations in the Injector Chain

Linac3 ion intensity

Linac3 is expected to deliver up to 50 μA Pb^{54+} (after stripping); this requires upgrading of the source [5]. Only with 70-turn injection into LEIR (with high efficiency through stacking in all three phase planes) can the nominal intensity per Linac pulse be attained. An RF cavity in the Linac3-LEIR line ramps the beam energy during the 200 μs pulse to enable stacking in the longitudinal phase plane.

Space charge in LEIR, PS, SPS

Space charge at injection field in LEIR, PS, SPS, leads to a spread in betatron tunes (space charge detuning ΔQ) and straddling of resonances, followed by emittance blow-up and eventually particle loss. Assuming a Gaussian distribution in all three phase planes, the vertical space charge tune shift (spread) of the central particle is

$$\Delta Q_y(0,0) \;=\; \frac{Z^2}{A}\frac{r_p N_b R}{\sqrt{2\pi}\,\beta\gamma^2\varepsilon_{y,n}\sigma_l}\left\langle\frac{1}{(1+(a(s)/b(s))}\right\rangle \tag{33.1}$$

where Z, A are the ions' charge state and the mass number, respectively; N_b the number of ions per bunch; R the machine circumference/(2π); β and γ relativistic factors; $\varepsilon_{y,n}$ is the normalised vertical rms emittance; σ_l the rms bunch length (bunch assumed Gaussian); a(s) and b(s) are horizontal and vertical beam sizes along the circumference.

Tune spread ΔQ

ΔQ is a tune spread rather than a shift because (i) the transverse Gaussian distribution renders the individual particle tune strongly dependent on its respective betatron amplitude; (ii) the synchrotron motion moves the particles periodically towards the head and tail of the bunches (lower density, smaller ΔQ), passing through the high density centre (large ΔQ); note that the "central" (in 6D phase space) particle features the largest value. Space charge is strongly decreasing with increasing beam energy but – somewhat surprisingly - is still critical in the SPS where the bunches are very short (~1 ns rms). The LEIR minimum ejection energy is dictated by the maximum tolerable ΔQ in PS of ~0.20, corresponding to a magnetic rigidity of about 4.2 Tm for Pb, while the PS has to accelerate the beam to maximum magnetic rigidity (86.7 Tm) to cope with the SPS space charge limit.

RF systems

While the large-band (frequency swing ~10) LEIR RF system is a new development, the PS and SPS will use existing RF systems to save resources and avoid adding to their respective impedance budgets. In particular, the hardware installed in the PS for protons to generate 4 ns bunches will be employed for ions as well. The choice of the ion bunch spacing of 100 ns in the LHC has been driven, among other aspects, by this type of consideration, but its generation requires elaborate RF gymnastics in the PS.

Vacuum: dynamic pressure and ion losses

The ions charge state may change due to interaction with the rest gas (LEIR, PS) or by electrons captured when ions interact with the cooling beam (LEIR). These ions are lost instantly and will in turn desorb molecules from the vacuum pipe surface, thus further increasing the pressure. In order to guarantee a beam life-time of ~30 s as required for accumulation in LEIR, the dynamic pressure has to be in the 10^{-12} mbar range, necessitating bake-out, beam scrubbing, loss localisation and possibly installation of getters in high-loss zones [6]. The higher LEIR-PS transfer energy helps reducing these losses in the PS as charge exchange cross sections are lower.

33.2.2 Injector chain overview

The LHC injector chain for ions is sketched in Fig. 33.1, including the principal ingredients of the upgrading programme [7, 8, 9] and its key parameters are compiled in Tab. 33.2.

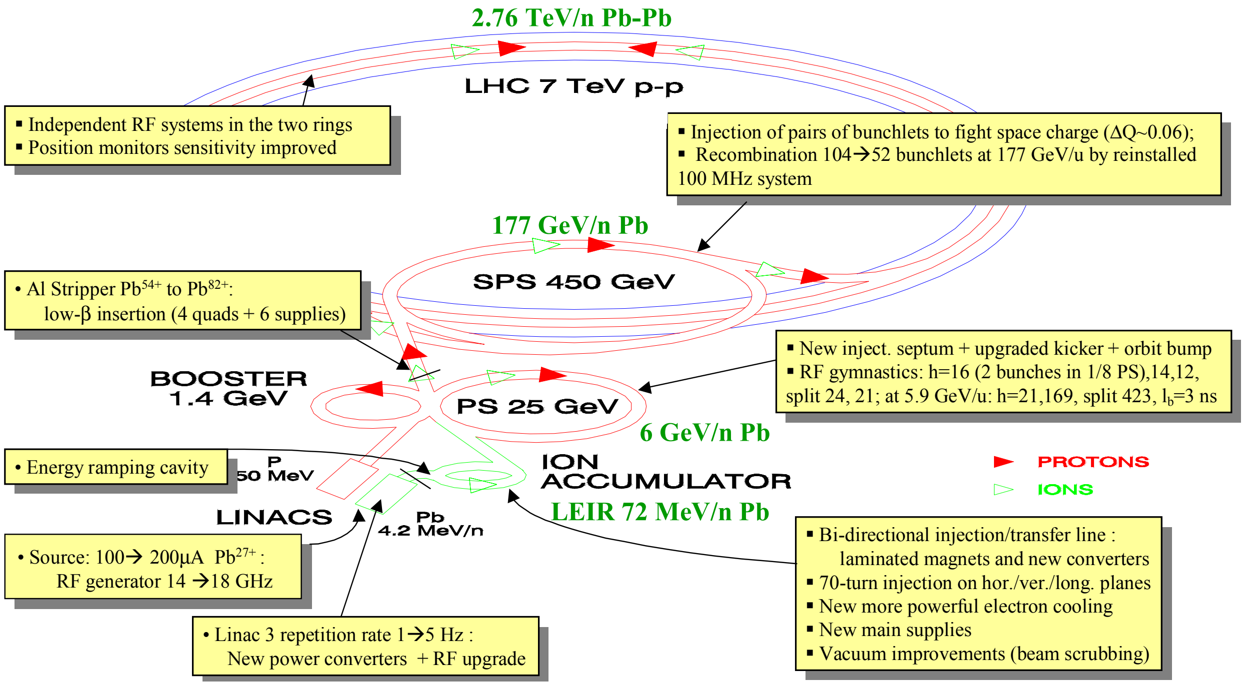

Figure 33.1: Overview of the LHC ion injector chain

Stripping

There are two stripping stages: one is a thin C foil at the Linac3 output, generating several adjacent charge states, amongst them Pb^{54+} produced with ~16% efficiency; the other one, an Al foil in the PS-SPS line, generates a fully-stripped Pb^{82+} beam. For the latter, the tight transverse emittance budget requires the implementation of a “low-β-insertion” at the foil to minimise emittance blow-up due to Coulomb scattering.

Table 33.2: LHC ion injector chain: key parameters for Pb ions at extraction energies

	Linac 3	LEIR	PS	SPS
Output energy	4.2 MeV/n	72.2 MeV/n	5.9 GeV/n	176.4 GeV/n
^{208}Pb charge state	27+/54+[1]	54+	54+/82+[1]	82+
output Bρ [Tm]	2.28/1.14[1]	4.80	86.7/57.1[1]	1500
number of batches to fill following machine	4-5	1	13,12,8	12
bunches per ring		2 (1/8 PS)	4 or 4x2[2]	52,48,32
ions per pulse[3]	1.15×10^{9}	9×10^{8}	4.8×10^{8}	$<4.7\times10^{9}$
ions per LHC bunch	1.15×10^{9}	2.25×10^{8}	1.2×10^{8}	9×10^{7}
bunch spacing [ns]		350	100 or 95/5[2]	100
ε^*_{rms} (= $(\beta\gamma)_{rel}\,\sigma^2/\beta_{twiss}$) [$\mu$m]	0.25	0.7	1.0	1.2
ε_{long} [eVs/n]		0.05	0.05/0.025[2]	0.24[4]
ε_{long} per LHC bunch [eVs/n]		0.025	0.05	0.24
4σ bunch length [ns]		200	3.9	1.65
2σ rel. momentum spread[2] $(\Delta p/p)_{2\sigma}$	0.4×10^{-3}	1.2×10^{-3}	6.5×10^{-4}	5.8×10^{-4}
repetition time [s]	0.2-0.4	3.6	3.6	54
space-charge ΔQ at injection		0.07[5]	0.17	0.082/0.041[2]

[1] stripper stages between Linac 3 and LEIR and between PS and SPS; parameters before/after stripping

[2] with splitting into four pairs of bunchlets at PS extraction to ease space charge in the SPS

[3] Linac3 pulse: 50 μA x 200 μs of Pb^{54+} after stripping at 4.2 MeV/n

[4] In SPS and LHC convention for Pb^{82+}: 1 eVs/n ≈ 2.5 eVs/charge

[5] After RF capture in LEIR

Bunchlets

Optionally, the 4 PS bunches are split into 4 pairs of bunchlets, each featuring ½ of the nominal population, reducing the space-charge tune spread in the SPS to ~0.05. The four bunchlet pairs are recombined to four bunches before extraction from the SPS. This splitting is not part of the baseline programme, because the space-charge limit of the SPS is not very well established and a subject of further studies [10].

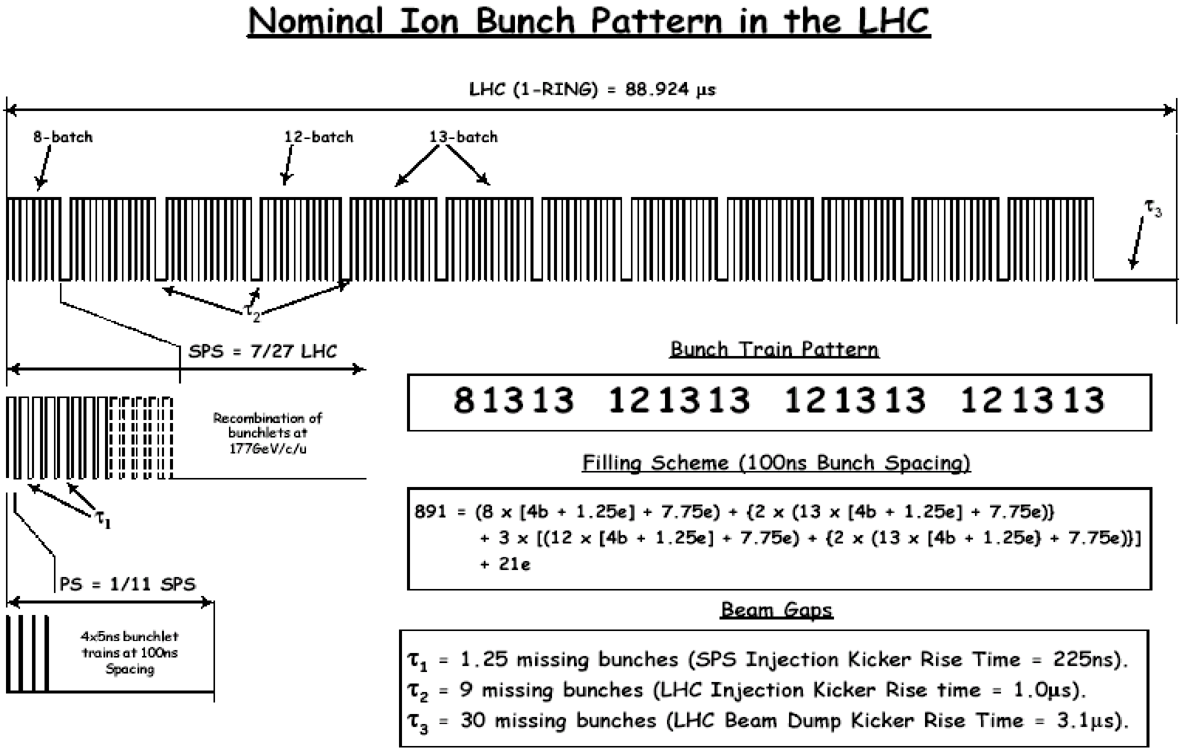

Figure 33.2: Lead ion bunch pattern for baseline filling scheme in PS, SPS and LHC.

Efficiency, emittance budget

The overall efficiency of the scheme (from Linac3 output after stripping to LHC store) is ~6%. The emittance budget (physical emittances) in the chain is as tight as the one for protons. This implies that beam instrumentation and dampers have to do their job equally well at the much lower ion intensities, which is a big challenge. By contrast, the SPS and LHC machines require large longitudinal emittances to lower the IBS growth rates. Therefore the longitudinal emittance budget is much more generous, to the point where controlled blow-up has to be used in these machines.

Filling the LHC, bunch pattern

The LHC filling time with Pb ions will be about 10 minutes/ring. The baseline Pb ion bunch pattern in PS, SPS and LHC machines is sketched in Fig. 33.2.

33.3 EARLY LEAD ION OPERATION SCHEME

The base-line (nominal) Pb ion injectors scheme will still be subject to basic limitations, some of them hard-edged and well defined, others only known after running-in of the accelerators concerned, including the LHC. In order to minimise the risk of these limitations jeopardising performance or even destroying LHC equipment in the initial ion-ion phase, an "early" lead operation scheme was proposed and adopted at the 2003 Chamonix Workshop [11]. First, this scheme is much easier to implement within the tight time schedule and second, it enables early studies on limiting phenomena in the ion chain without potentially disastrous consequences, in particular quenches in the LHC. Thirdly, even the much lower luminosity (~factor 20) would enable the experiments to fully exploit the early discovery potential of Pb-Pb collisions in the LHC. This factor ~20 in luminosity ($L_0 = 5\times10^{25}$ cm^2 s^{-1}) is due to a reduction of the number of bunches by a factor 10 (~60 instead of ~600 per LHC ring) and by increasing β^* by a factor 2 (0.5 to 1 m). However, the number of ions per LHC bunch is the same as in the base-line scheme, 7×10^7 Pb ions/bunch.

Table 33.3: Rationale behind the early lead scheme

Limitation of Baseline (Nominal) Lead Scheme	Change in Early Lead Scheme	Comments
Accumulation of 4 Linac pulses in LEIR yielding 9×10^8 ions per LEIR cycle	1 Linac pulse is sufficient to produce 2.5×10^8 ions/LEIR pulse	No accumulation in LEIR; LEIR/PS cycle 2.4 instead of 3.6 sec
Very elaborate RF gymnastics in the PS with complicated beam control	PS accelerates just one bunch on h=16. No splitting into bunchlet pairs.	Beam control very much easier, with larger chances for swift commissioning
SPS injection plateau 42 s long because up to 13 PS batches accumulated	SPS injection plateau 7 s with only 3 or 4 PS batches accumulated	Less losses caused by IBS and RF noise on SPS injection plateau
Injection of bunchlet pairs in the SPS so as to halve its space charge ΔQ to 0.05	No splitting in the PS, further simplifying RF gymnastics	SPS space charge ΔQ of ~0.1 acceptable on shortened injection plateau?
Recombination of bunchlet pairs in SPS before extracting to the LHC	Not required (hopefully)	Re-installation of existing 100 MHz system in the SPS postponed
LHC BPM sensitivity $> 2\times10^7$ Pb ions/bunch	Intensity 7×10^7 p/bunch as in nominal (baseline) scheme	BPM's do their job with the early scheme as well
LHC quench limit due to ECPP[1] at $L < 10^{27}$ cm^{-2} s^{-1}	With $L_0 = 5\times10^{25}$ cm^2 s^{-1}, studies without risk possible	ECPP proportional to luminosity, thus early scheme far from quench limit.
Luminosity lifetime short	Much longer with lower L_0	
Bunch spacing 100ns	Bunch spacing ~1.35 μs	Kicker rise times not an issue

[1] Electron Capture after Pair Production: possible cause for magnet quenches, potentially limiting L_0

The reasons why this early Pb ion scheme is easier to implement and the limiting phenomena which can be studied without risks are presented in Tab. 33.3. The early Pb ion scheme with its most salient features is depicted in Fig 33.3. In short, this scheme aims at a simplified setting-up of the injector chain while postponing the commissioning of the baseline (nominal) scheme in order to (i) alleviate the risk of material damage; (ii) remove the tight constraints on the running-in schedule; (iii) provide an opportunity to study limiting phenomena under less pressure.

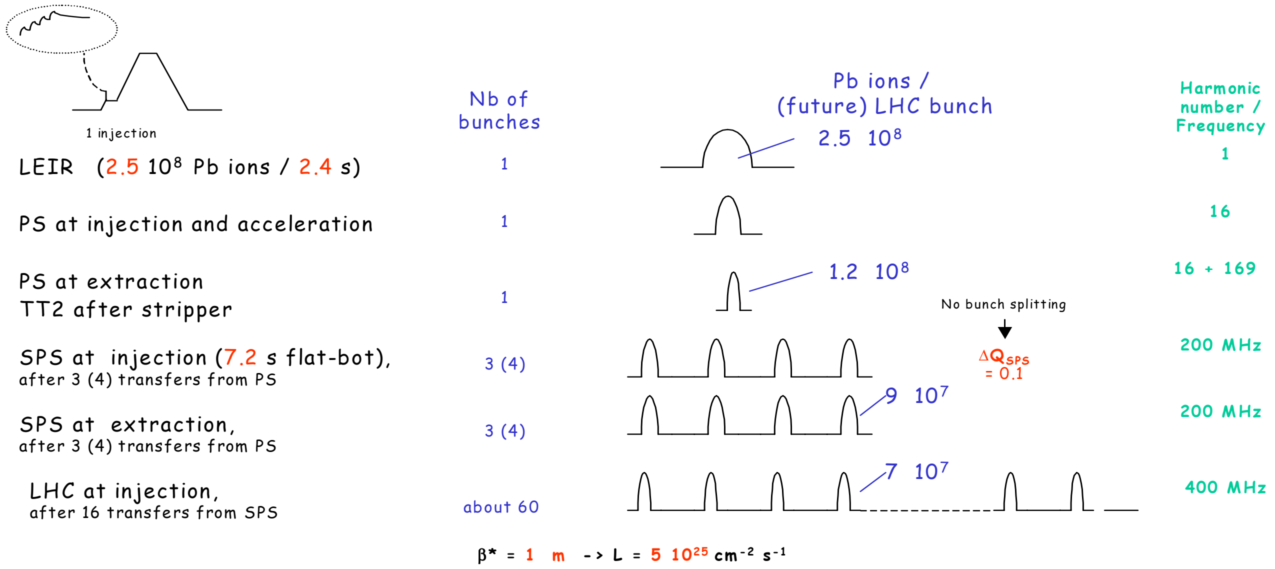

Figure 33.3: Early Pb ion operation scheme, basic features

33.4 INJECTOR CHAIN, OTHER VARIANTS

The upgrading of LEIR is a major endeavour and the resources for its exploitation are not negligible, therefore schemes to provide the LHC with ions via the PSB but without LEIR (no phase space compression) were explored: (i) Pb ions from an ECR source; (ii) Pb ions from a Laser Ion Source (LIS); (iii) Oxygen ions from an ECR source. Research into LIS has been discontinued recently as results obtained so far, though interesting, are far from satisfying the stringent LHC requirements. The two other schemes were assessed (Tab. 33.4) based on past experience with the oxygen and lead fixed-target programmes as well as some dedicated beam tests in the PSB [12].

Table 33.4: Estimated LHC performance with Pb or O via the PSB, without LEIR

Scenario	charges /bunch in LHC	ions/bunch in LHC	L_0 [cm^{-2} s^{-1}]	comments
Pb^{82+}, via PSB (upgraded ECR)	2.4×10^8 (BPM “blind”)	2.9×10^6	1.7×10^{24} (ALICE “blind”)	$L_0 > 10^{25}$ required by ALICE
O^{8+} via PSB[1] (upgraded ECR)	6.1×10^9	7.6×10^8	1.2×10^{29}	OK but ALICE not interested
Pb^{82+}, via LEIR	*5.7×10^9*	*7×10^7*	*10^{27}*	*for reference*

[1] During an oxygen run, no protons can be sent to the PSB in pulse sharing mode, unless the Linac2 to PSB line undergoes a major upgrade.

Whereas the Pb scenario with the PSB is well below useful LHC performance, the oxygen scheme would be adequate, but the physics with these light ions does not appear attractive. However, the option should be kept in mind as a fallback solution. Fig. 33.4 sketches the LHC performance with the “baseline” and “early” Pb schemes, as well as the two scenarios via the PSB (Pb, O) in an intensity/luminosity diagram; major limiting effects are shown as well. The small working area in terms of intensity/bunch is highlighted.

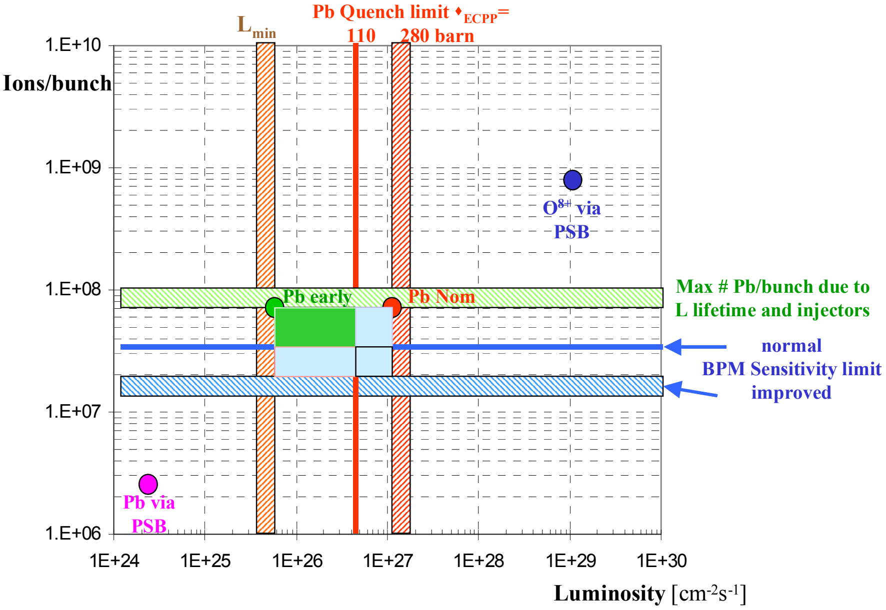

Figure 33.4: LHC performance with injector scenarios based on LEIR (Early and Nominal = Baseline) or the PS Booster (ECR source performance improved).

33.5 FUTURE OPTION: LIGHTER IONS

The LHC ion physics programme is based on Pb ions for the first three to four years of operation. Therefore the “baseline” project to prepare the LHC ion injectors is exclusively dealing with lead ions. However, after this period, physicists envisage studying Pb-p collisions, for which two independent RF systems are being built for the LHC rings. A few years later, collisions between lighter ions (favoured are mainly Ar and to a lesser extent Kr, In, O, see Table 33.5) will be requested in order to vary the energy density obtained in collisions and thus to improve understanding of the quark-gluon plasma [1].

Table 33.5: Typical lighter ions envisaged for the future LHC programme

Element	A	charge state Z in SPS, LHC (fully stripped)	charge state in LEIR, PS	initial luminosity L_0 probably limited by
In	115	49	37	space charge PS, SPS or LHC quench limit
Kr	84	36	29	space charge PS
Ar	40	18	16	space charge PS
O	16	8	8	space charge PS

In earlier proposals, lighter ions were considered as part of the base-line scheme and treated in much detail accordingly [2, 13]. This paradigm has now changed and the lighter ions are considered as an improvement programme. Several of the limitations will be much better known once the LHC works with lead ions and five years should be sufficient to upgrade and optimise the ion injector for Ar, Kr, In and O, in the light of these findings. Each of the ions will require a separate, unique mode of operation and possibly hardware changes, as most of the parameters and limitations strongly depend on the ion chosen.

To get an idea about what performance one can expect with lighter ions, one starts with a very simple (and pessimistic) assumption: with the ions fully stripped, the number of charges per bunch at collision is invariant. For example, with the same charge per bunch, there would be ten times more O^{8+} than Pb^{82+} ions per bunch and 100 times higher luminosity. In fact, the luminosity for lighter ions will be much better than in this model (one or two orders of magnitude) for the following reasons:

- The cross section for nuclear effects during collisions is much lower for lighter ions, so ECPP will probably not limit LHC performance for ions lighter than In.
- Intra-Beam Scattering may be a stumbling block on the SPS and LHC injection plateaus as well as during LHC collisions. The effect scales with $(Z^2/A)^2$, so lighter ions suffer less.
- Space charge: the figures for the tune spread ΔQ (Eq. 33.1) anticipated for Pb (Table 33.2) are seriously limiting the performance in LEIR, PS, SPS. Here the factor Z^2/A also helps for lighter ions.

- The ECR source tends to favour lighter ions in the sense that more charges are produced. Future tests with the upgraded ECR source will provide actual figures.
- Stripping efficiencies between Linac3 and LEIR are better for lighter ions.
- With a lower electron capture cross section for a given energy, lighter ions will suffer much less from losses due to interactions with the rest gas in LEIR and PS.
- The only effect favouring heavy ions is the synchrotron radiation damping time which scales as A^4/Z^5 (A is the mass and Z the charge of the ion) for a given magnetic rigidity (see Vol. 1, Chap. 21); synchrotron radiation damping is fastest for lead.

In general, the hardware upgrades of the ion injector chain have been designed without any other ion than Pb in mind. As an exception to this rule, two important parameters have sneaked into the baseline project in view of performance with lighter ions:

- PS injection energy: the lead extraction energy of LEIR has been set to 72 MeV/n (magnetic rigidity 4.8 Tm). At this energy, the space charge tune spread ΔQ of the nominal Pb beam at PS injection is 0.17 (Tab. 2.1), somewhat smaller than the estimated PS limit of about 0.20 - 0.25, thus 55 MeV/n (4.2 Tm) would have been sufficient for Pb. The energy of 72 MeV/n coincides with the lower frequency limit of the PS cavities with h=16, corresponding to two bunches (h=2) from LEIR. Moreover, it provides some margin for the Pb beam. Note that the higher magnetic rigidity will reduce space charge in the PS for lighter ions which is their overall performance bottleneck as suggested in Tab. 33.5.
- RF cavities with large frequency range: acceleration in LEIR requires a frequency range of about 0.7 to 2.8 MHz for Pb^{54+}, whereas the required range extends to 4.7 MHz for light ions ($Z/A \leq 0.5$). The new cavities, equipped with a novel core material, will not be tunable but broad-band (0.4 – 4.7 MHz) thus enabling light ions to be accelerated in LEIR to a magnetic rigidity of 4.8 Tm, as the lead ions. A further asset of this choice is the possibility of superposing several RF signals into the same cavity.

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